The POP Ocean Model in the CESM

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starting with slides borrowed from Susan's tutorial presentation:

Ocean Modeling I

The Parallel Ocean Program (POP)

Susan Bates
NCAR

first version of "CSM" was based on GFDL's MOM.1 ocean model. Switched over to LANL's POP for CCSM.2

Topics

- Obstacles for ocean modeling
- Difference between ocean and atmosphere modeling
- What about the ocean is important to climate
- Equations of motion
- Ocean model grid
- Timescales of flow
- ~~Advection schemes~~
- ~~Air-sea coupling~~

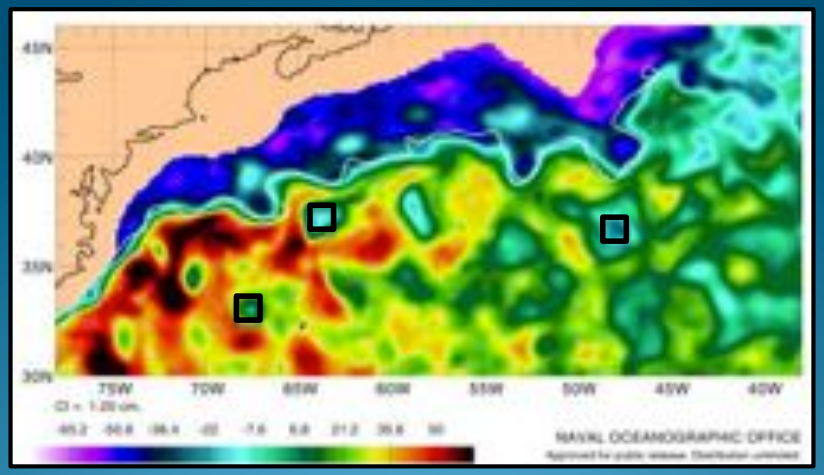
Ocean Modeling Obstacles

Irregular Domain

Ocean Modeling Obstacles

Spatial Scales of Flow

Eddy length scales <10km



Ocean Modeling Obstacles

Equilibration Timescale

Scaling argument for deep adjustment time :

$$H^2/\kappa = (5000m)^2 / (10^{-5}\ m^2/s)$$
$$= O(10{,}000\ years)$$

Bottom Line for Climate

-Equilibrium at eddy resolution can't be reached
- Must parameterize most energetic flow

Differences between Ocean and Atmosphere

- No change of state of seawater – makes it much easier. Just form ice when temperature <-1.8°C
- The density change from top to bottom is much smaller – 1.02 to 1.04 gm/cc. This makes the Rossby radius much smaller – 100s to 10s km.
- The ocean is a 2 part density fluid (temp and salt).

Differences between Ocean and Atmosphere

- There is extremely small mixing across density surfaces once water masses are buried below the mixed layer base. This is why water masses can be named, and followed around the ocean.
- Top to bottom lateral boundaries. Leads to WBC (heat transport) leaving little for eddies.
- The heat capacity of the ocean is much larger than the atmosphere. This makes it an important heat reservoir.
- The atmosphere contains more intrinsic variability than the ocean. The ocean is primarily forced by the atmosphere.

What is needed from the ocean to get climate change correct?

- Air-sea coupling (sst feedbacks).
- Need to get heat uptake correct.
- Need good representation of meridional transport of heat (and other properties): circulation, including the meridional overturning circulation (MOC).
- Representation of carbon cycle (storage of CO_2 (uptake), $CaCO_2$): Need a good vertical mixing scheme to get correct mixed layer depths and upwell nutrient rich water.

this is **not** an exhaustive list!

Primitive Equations

7 equations in 7 unknowns :

{u,v,w} ,	3 velocity components
θ,	potential temperature
S,	salinity
ρ,	density
p,	pressure

Plus 1 equation for each passive tracer, e.g. CFC, Ideal Age

u, v, theta and S are prognostic

Primitive Equations

Momentum $$\frac{D}{Dt}\mathbf{u} + f\mathbf{k}\times\mathbf{u} + \nabla p = \nu_H\,\nabla^2\mathbf{u} + \nu_V\,\mathbf{u}_{zz}$$

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla + w\frac{\partial}{\partial z}$$

Hydrostatic $$p_z + g\rho/\rho_0 = 0$$

Continuity $$\nabla\cdot\mathbf{u} + w_z = 0$$

Temperature $$\frac{D}{Dt}\theta = \kappa_H\,\nabla^2\theta + \kappa_V\,\theta_{zz}$$

Salinity $$\frac{D}{Dt}S = \kappa_H\,\nabla^2 S + \kappa_V\,S_{zz}$$

Eqn of State $$\rho = \rho(p,\theta,S)$$

Tracer Equation $$\frac{\partial}{\partial t}\varphi + \mathcal{L}(\varphi) = \mathcal{D}_H(\varphi) + \mathcal{D}_V(\varphi)$$

$$\mathcal{D}_H(\varphi) = A_H\nabla^2\varphi$$

$$\mathcal{D}_V(\varphi) = \frac{\partial}{\partial z}\kappa\frac{\partial}{\partial z}\varphi,$$

Primitive eqns are Navier Stokes with "thin" approximation, plus hydrostatic approx.

POP in CCSM/CESM is run under the Boussinesq approx (treat density as constant, except in pressure)

Primitive Equations

- Continuity: can't deform seawater, so what flows into a control volume must flow out.
- Eqn of state: density dominated by T in upper tropical ocean; by S at high latitudes and deep.
- Hydrostatic: when ocean becomes statically unstable ($\rho_z>0$) => vertical overturning should occur, but cannot because vertical acceleration has been excluded. This mixing is accomplished by a very large coefficient of vertical diffusion.

Baroclinic & Barotropic Flow

- Issue : CFL stability condition associated with fast surface gravity waves.
  - $u(\Delta t/\Delta x) \leq 1$
  - Barotropic mode $\sqrt{gH} \sim= 200m/s$
- Split flow into depth average barotropic plus vertically varying baroclinic

momentum equations are split into the vertically averaged velocity (2-D) and the residual (3-D). This makes for quite a sticky mess!

Baroclinic & Barotropic Flow

- Solve the vertically integrated momentum and continuity equations for the barotropic mode with new unknowns

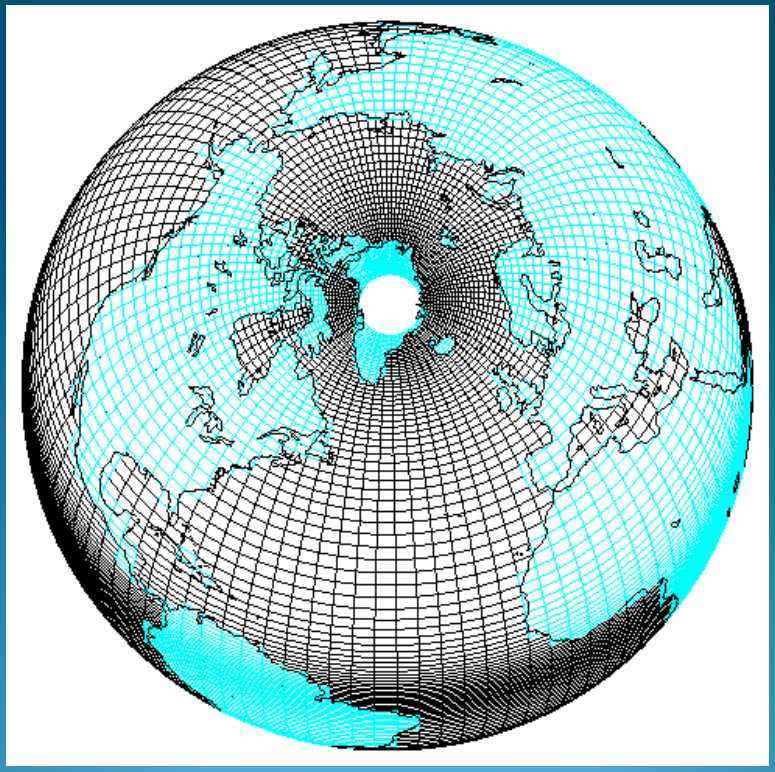
  η sea surface height

  $\langle U \rangle$ depth averaged flow

- 1st internal mode in baroclinic equations is of the order 2m/s, which sets the model timestep.

Model Grid

displaced pole



gx1
gx3

Model Grid

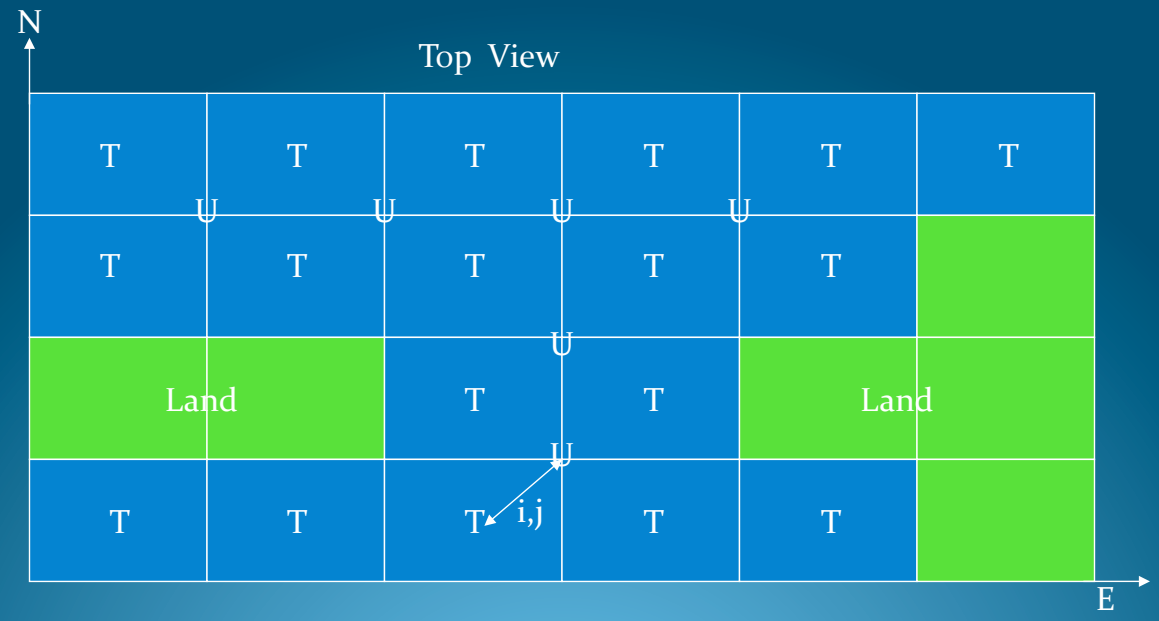
tripole

tx0.1

we use this tripolar grid for the strongly eddying global model (orders of magnitude more expensive to run this high resolution model)

Model Grid

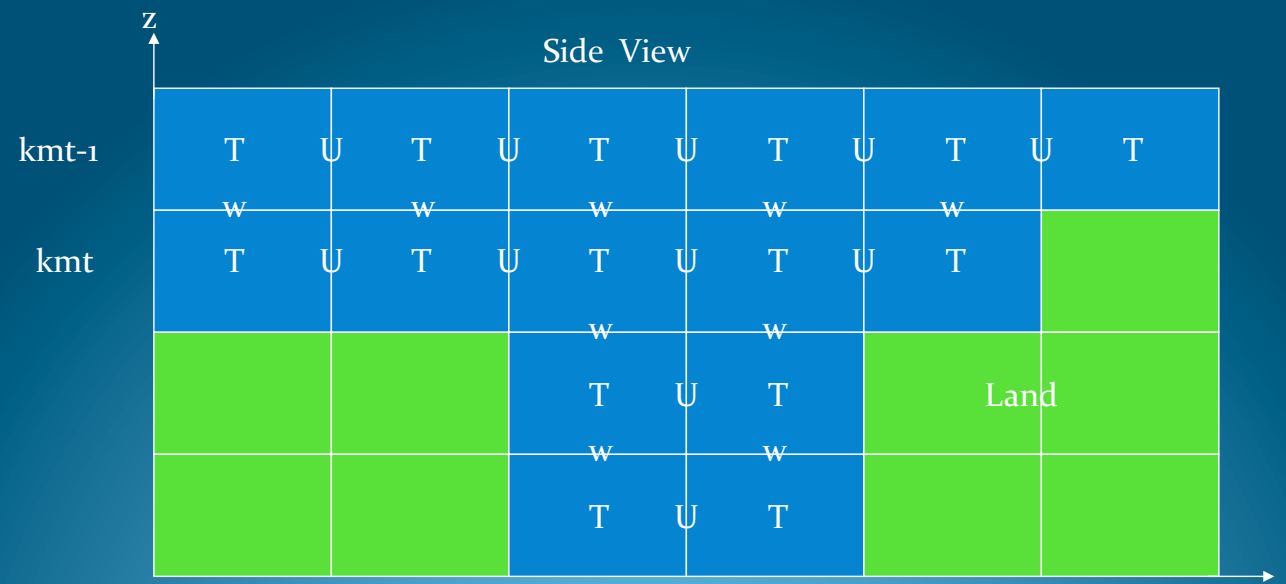
B-grid
T=tracer grid, U=velocity grid



staggering of grid must be taken into account in post-processing

Model Grid

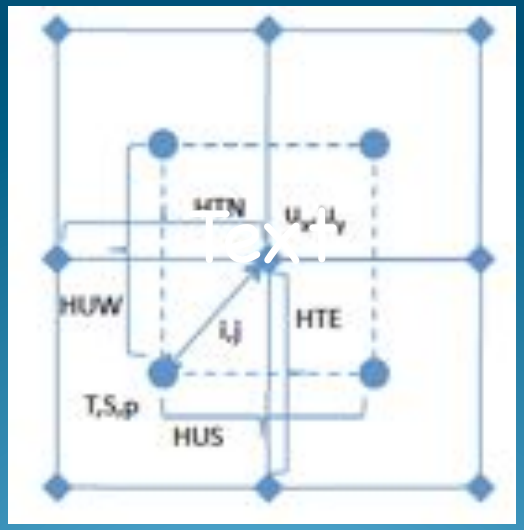
B-grid
T=tracer grid, U=velocity grid



also staggered in the vertical

if it's important to get these things right, then go to the POP.2 Scientific Reference Manual

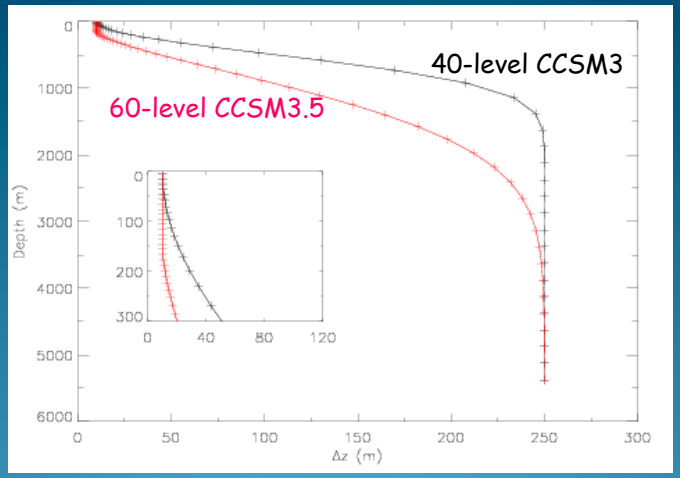
Model Grid



http://www.cesm.ucar.edu/models/cesm1.0/pop2/doc/sci/POPRefManual.pdf, R.D. Smith et al., LAUR-10-01853

Model Grid

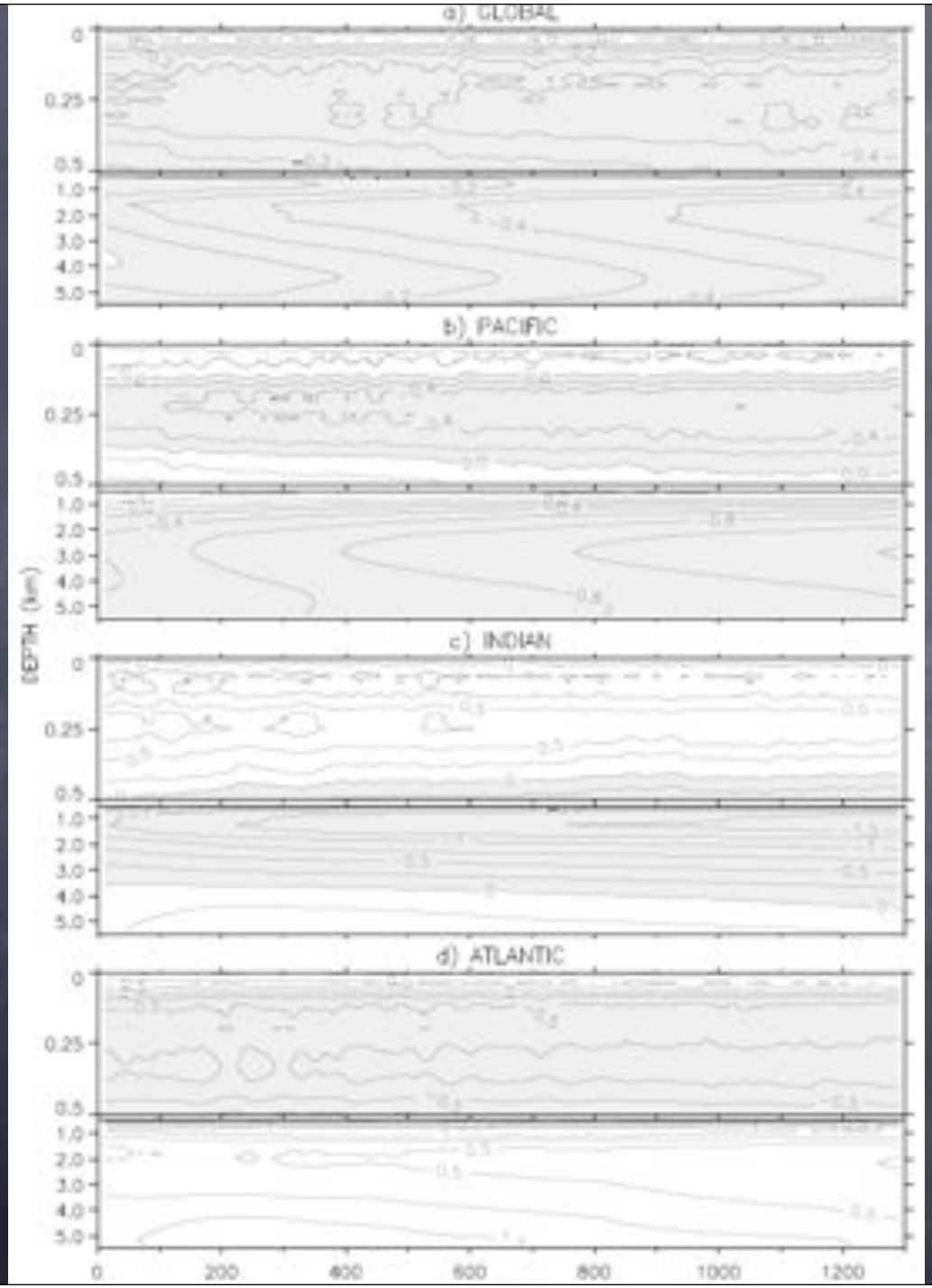
Vertical Grid



10m spacing in upper 160m, increasing to 250m in the deep ocean

What do we look at in the ocean model, to see if newer is better?

- The following is from "The CCSM4 Ocean Component", overview paper of Danabasoglu et al., submitted to J. of Climate.



← rate of deep cooling not slowing

Drifts in horizontally-averaged (potential) temperature, as a function of depth

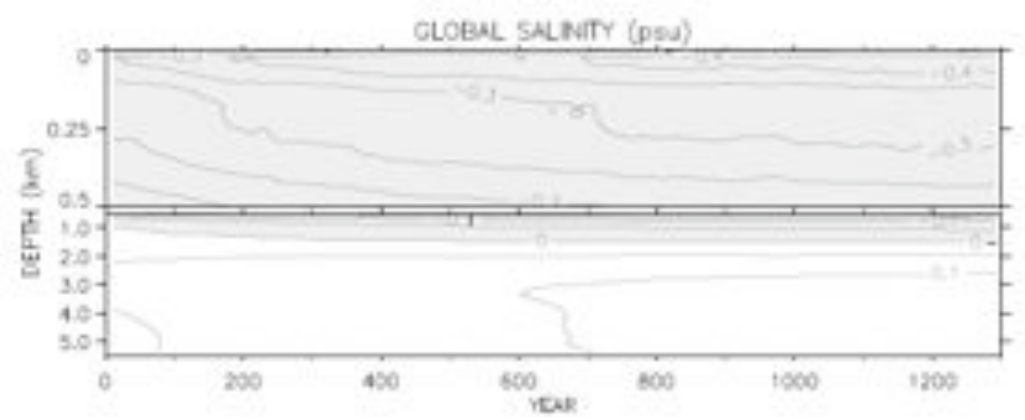


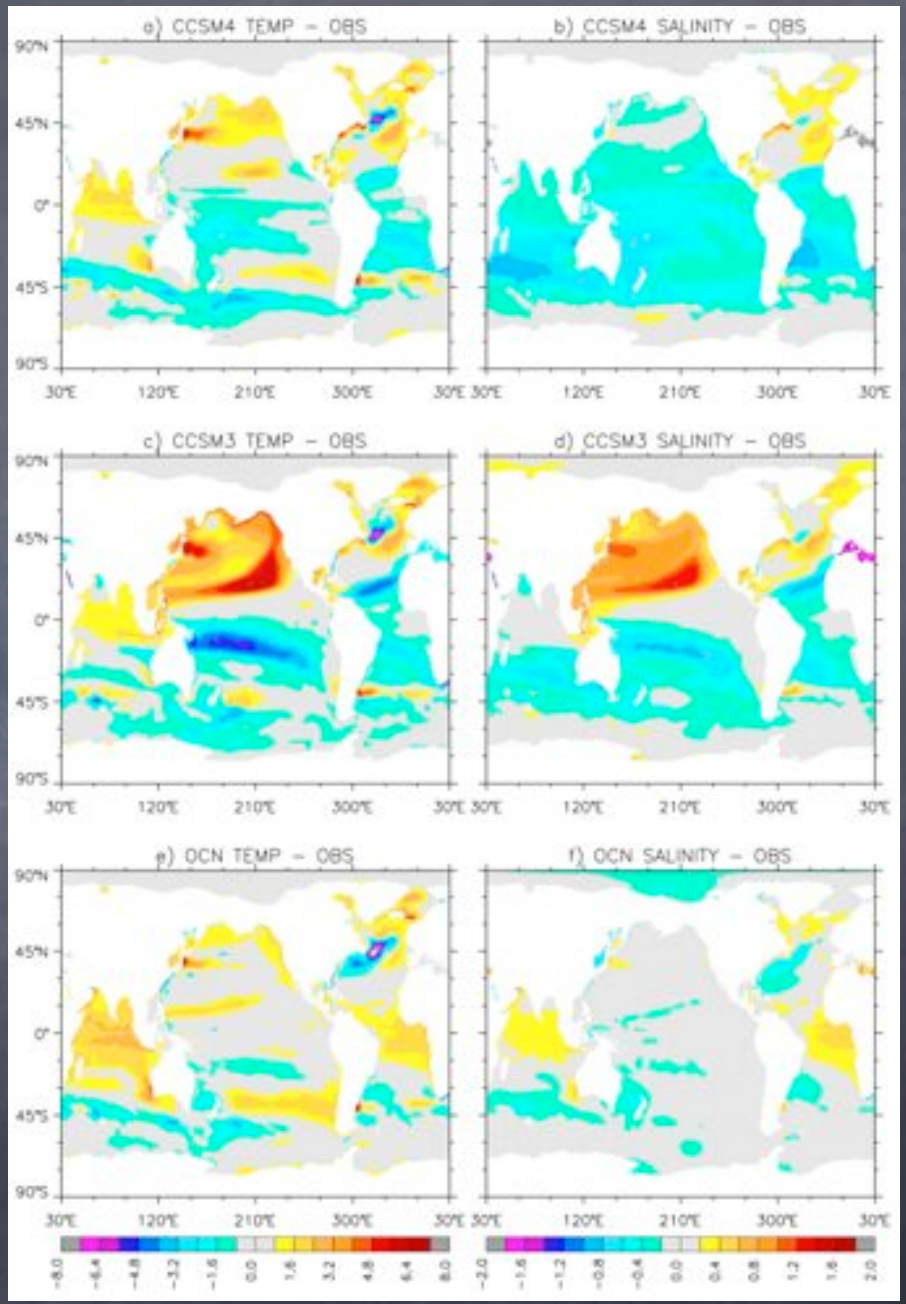
FIG. 3. Horizontal-mean salinity difference time series for 1850 CONTROL

the depths are also getting saltier

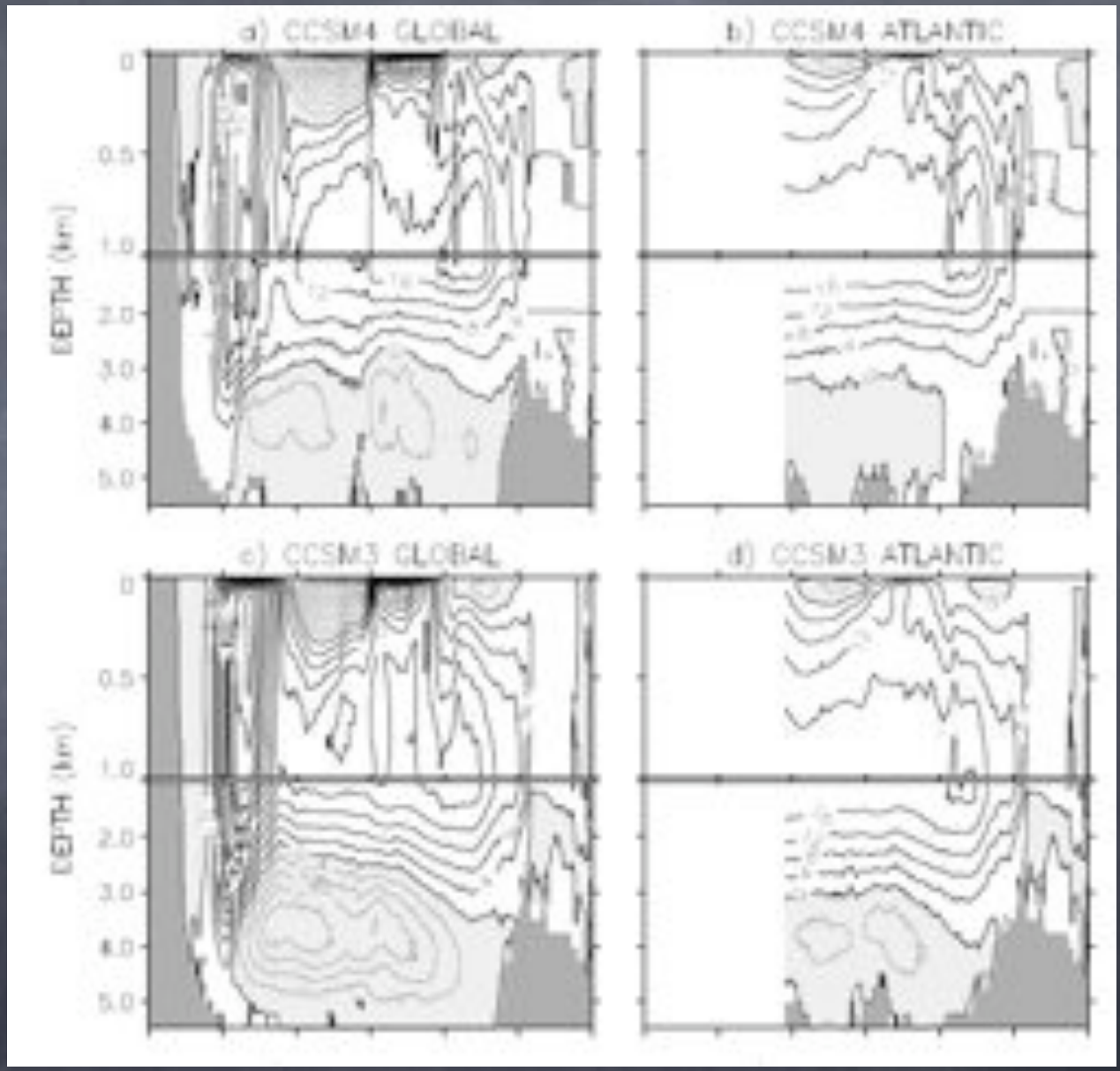
(saltier and colder means more dense)

root mean square temperature diff down from 1.36 oC to 1.14 oC

(this, mostly a reflection of spin-up procedure)



Overturning stream function (zonally integrated). Big difference in Antarctic waters (in grey, CCW in this view)



all good for upper ocean poleward flow. Not so good for the deep return flow.

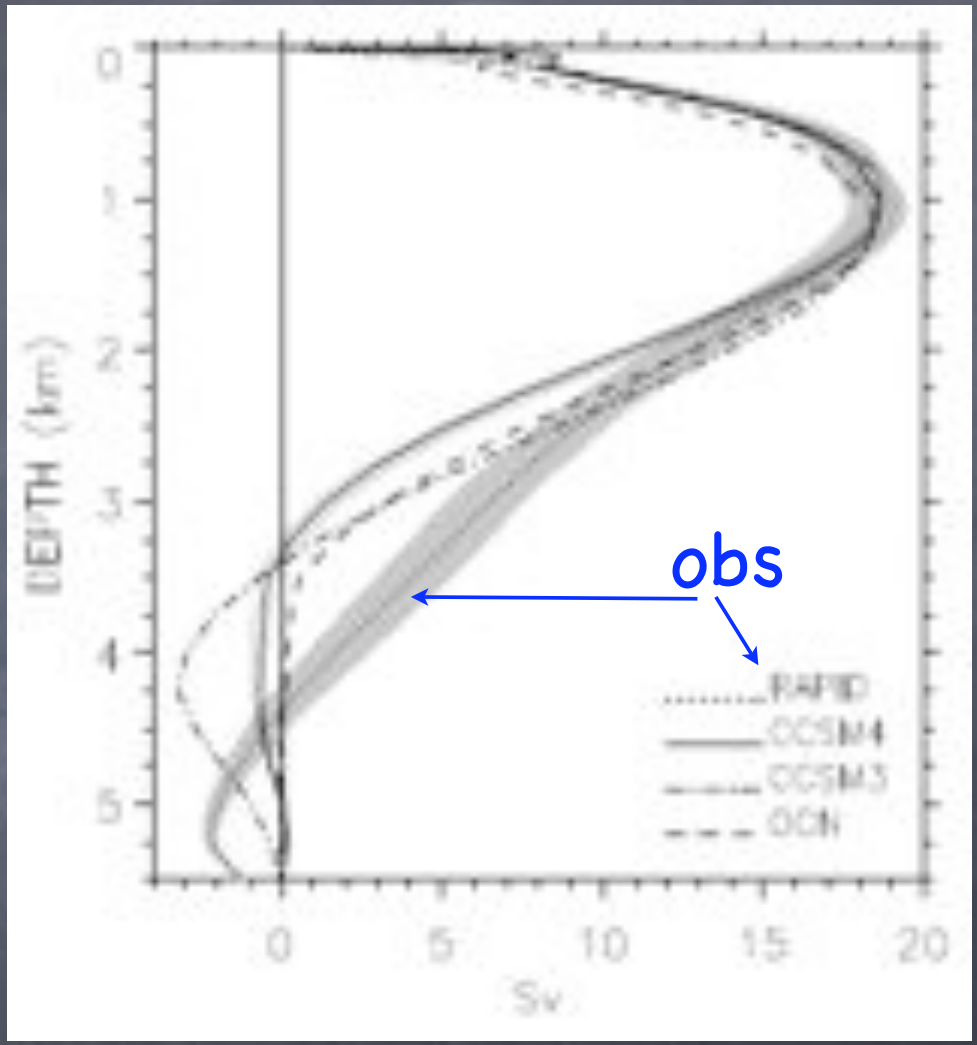


FIG. 11. Atlantic meridional overturning circulation profiles at 26.5°N from CCSM4, CCSM3, and OCN in comparison with the four-year mean RAPID data (April 2004 - April

Poleward heat transports: Getting the CCSM curves close to "obs" (grey swath) was a major success of first version of the CCSM (no more "flux correction").

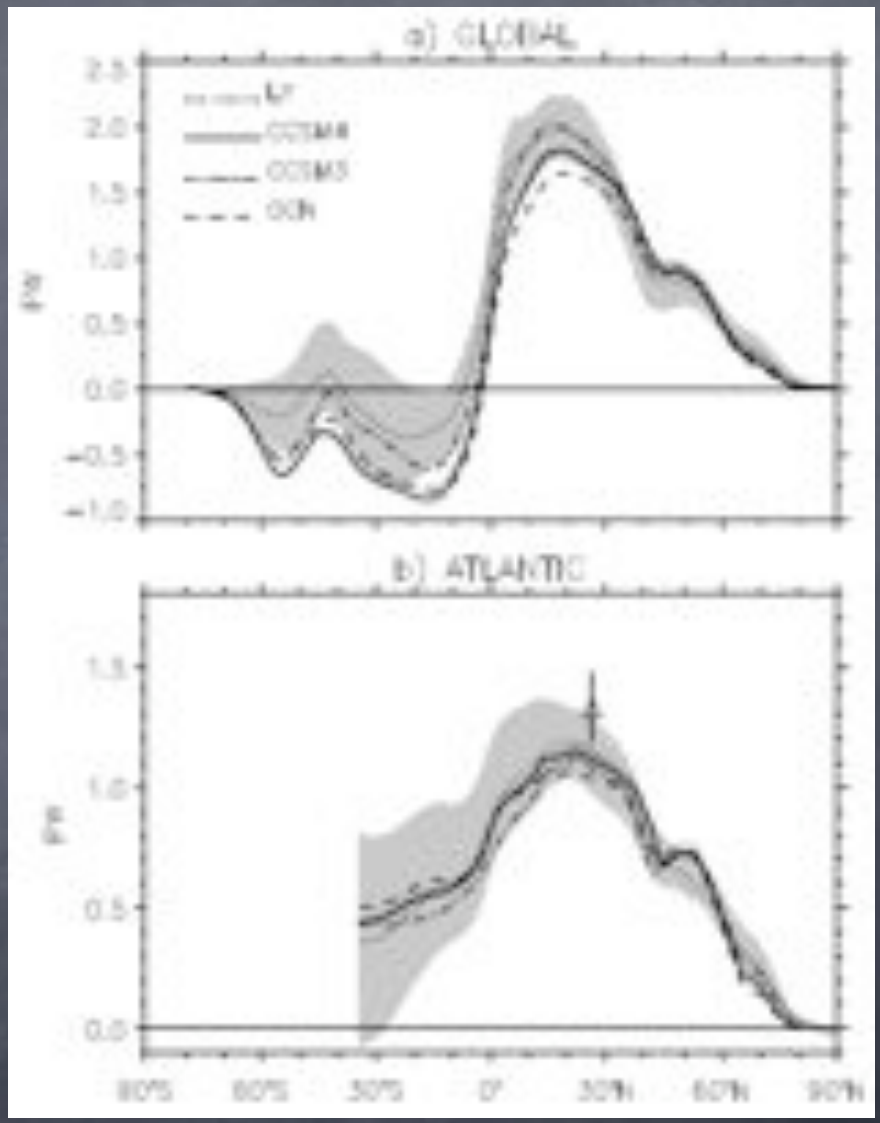


FIG. 12. a) Global and b) Atlantic Ocean northward heat transports.

Near-surface current structure of the equatorial Pacific is intricate.

It's important to tropical variability (ENSO), and was a major focus of work to improve from versions 1 to 2.

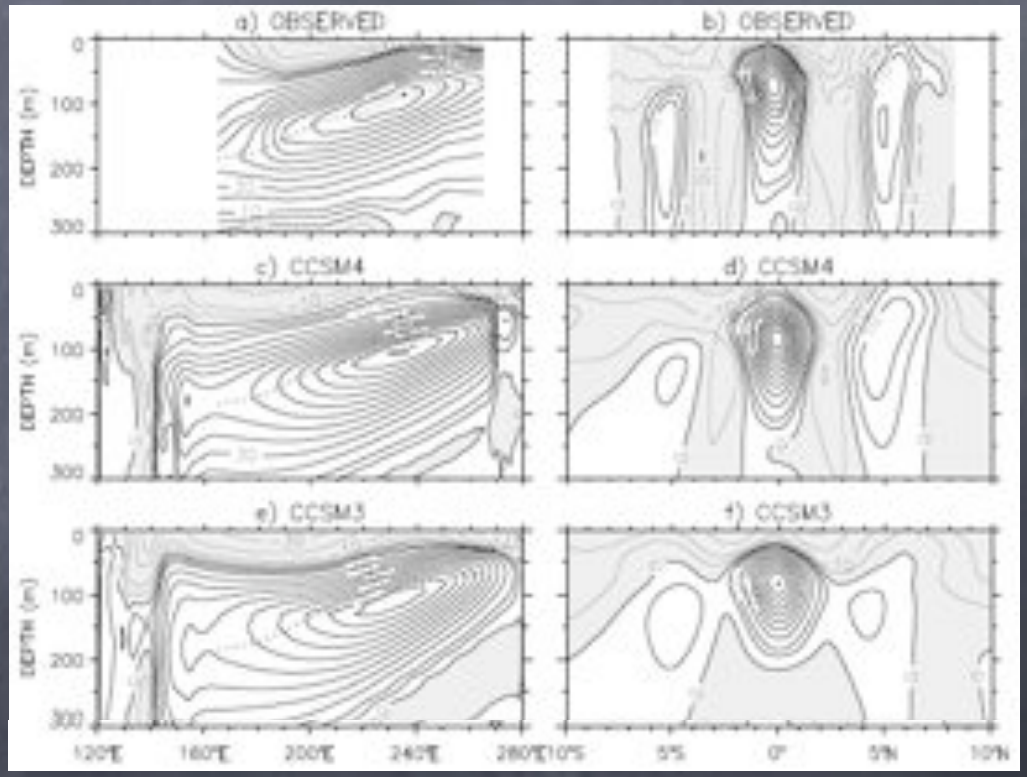


FIG. 15. Zonal velocity in the Pacific Ocean along the equator (left panels) and at 110°W (right panels). The observations are from Johnson et al. (2002). The regular contour interval

Bias reduction (not elimination) in the Northwest Atlantic.

Here, these are mixed layer depths.

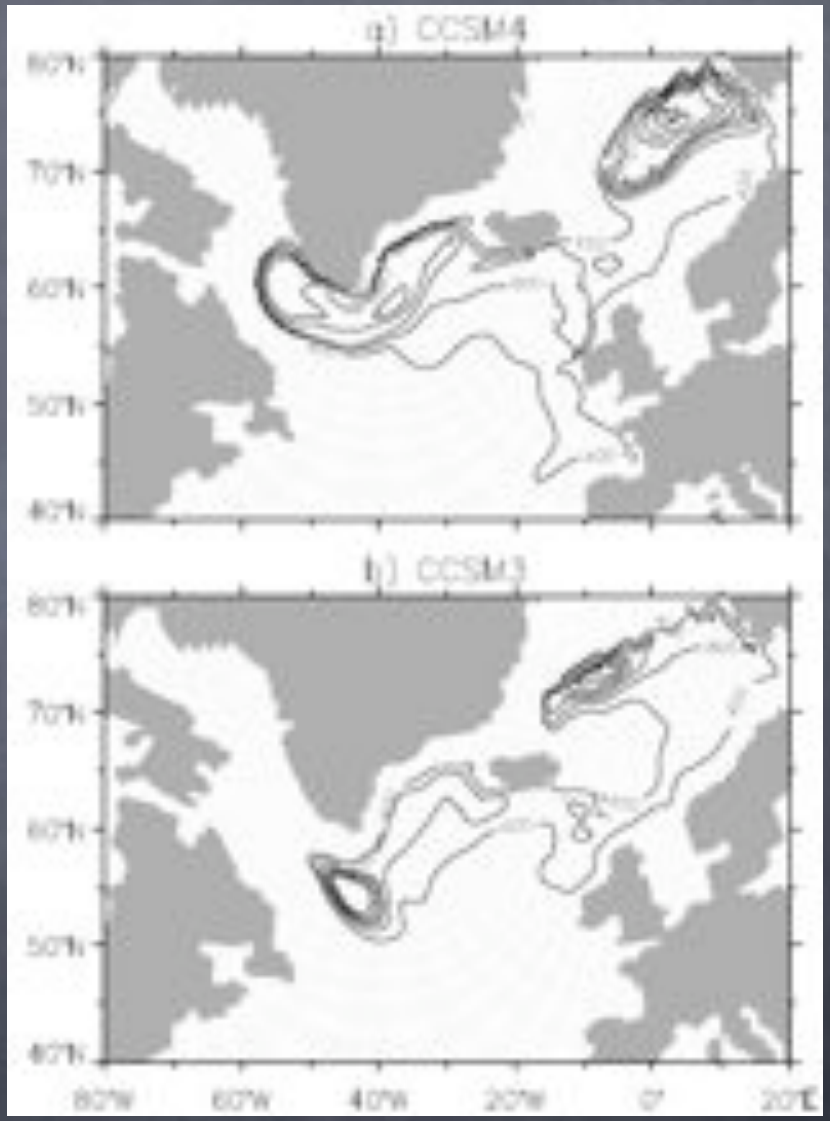
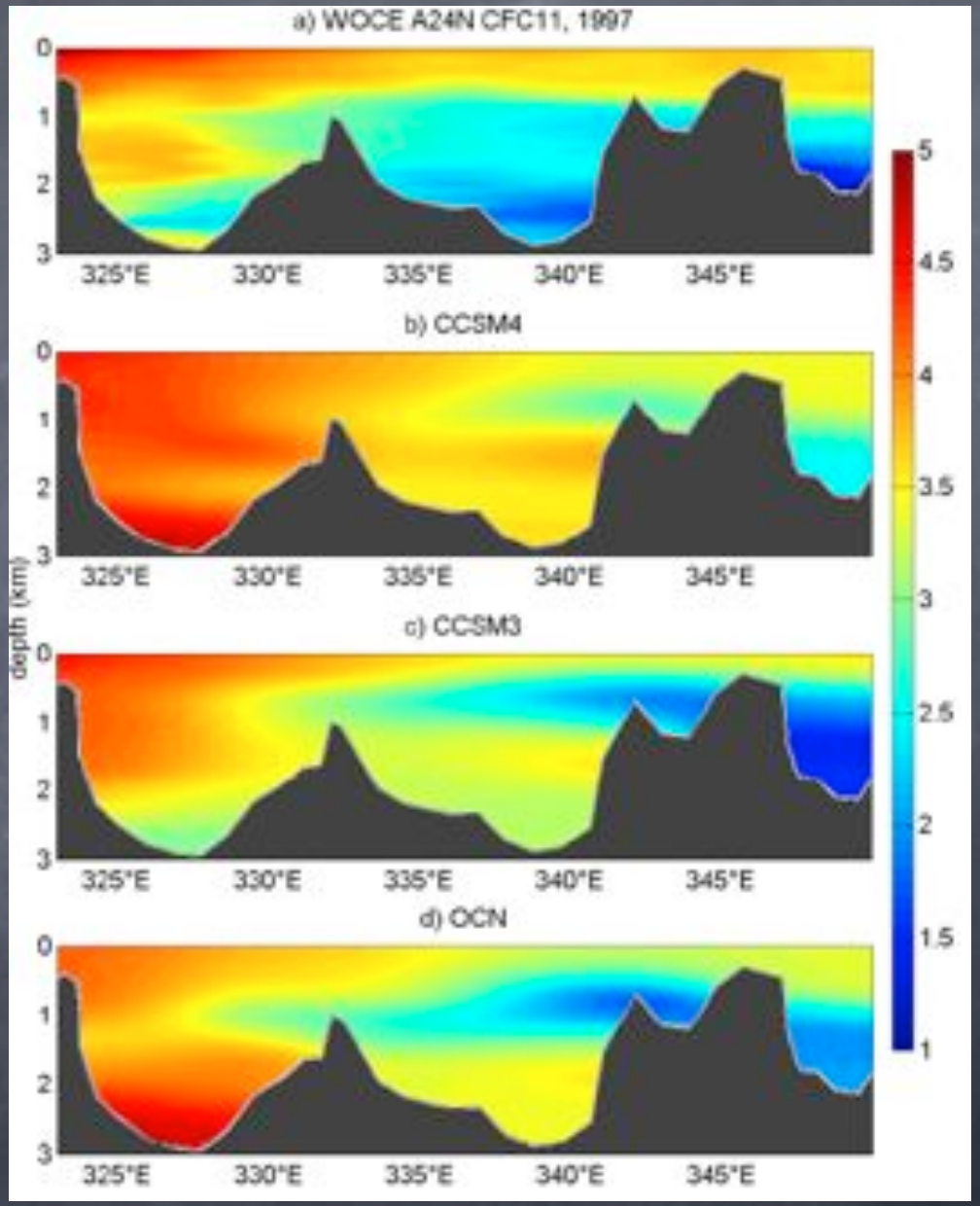


FIG. 18. Winter-mean (January, February, March) mixed layer depth

Chlorofluorocarbons (CFCs) act as inert tracers, tagging waters ventilated since ~1940s.

Does this indicate points that could yet be improved, or does it motivate the much more costly strongly eddying version of the model?



that was one short take on the ocean component

- more under CESM web site (look under models)
- more under LANL web site (http://climate.lanl.gov/)